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Complete List of Authors:	Ghandil, Mehdi; Isfahan University of Technology, Department of Civil Engineering Aldaikh, Hesham; University of Cambridge, Department of Engineering

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Damage-based Seismic Planar Pounding Analysis of Adjacent Symmetric Buildings Considering Inelastic Structure-Soil-Structure Interaction

Mehdi Ghandil[1], Hesham Aldaikh[2]

[1] Department of Civil Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran.
[2] Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, United Kingdom.

Abstract

In cities and urban areas, building structures located at close proximities inevitably interact under dynamic loading by direct pounding and indirectly through the underlying soil. Majority of the previous adjacent buildings pounding studies that have taken the Structure-Soil-Structure Interaction (SSSI) problem into account have used simple lumped mass-spring-dashpot models under plane-strain conditions. In this research, the problem of SSSI-included pounding problem of two adjacent symmetric in plan buildings resting on a soft soil profile excited by uniaxial earthquake loadings is investigated. To this end, a series of SSSI models considering one-directional nonlinear impact elements between adjacent co-planar stories and using a method for direct FE modeling of 3D inelastic underlying soil volume have been developed to accurately study the problem. An advanced inelastic structural behavior parameter, the seismic damage index, has been considered in this study as the key nonlinear structural response of adjacent buildings. Based on the results of SSSI and fixed-base cases analyses presented herein, two main problems are investigated, namely, the minimum building separation distance for pounding prevention and seismic pounding effects on structural damage in adjacent buildings. The final results show that at least three times the IBC 2009 minimum distance for building separation recommended value is required as a clear distance for adjacent symmetric buildings to prevent the occurrence of seismic pounding. At the IBC recommended distance, adjacent buildings experienced severe seismic pounding and therefore significant variations in storey shear forces and damage indices.

Keywords: Seismic planar pounding, storey damage index, storey shear force, adjacent symmetric buildings, structure-soil-structure interaction, IBC 2009 minimum distance for building separation provision.

1. Introduction

An increasing human population and the existence of a limited available habitable urban space has resulted in densely located buildings in most busy places. The concentration of tall buildings and skyscrapers in metropolises located in high seismic activity regions has made the occurrence of a special seismic phenomenon possible, i.e. the seismic pounding of adjacent structures. In the 1964 Alaskan earthquake, the 14-storey Westward Anchorage hotel building was damaged because of pounding to a shorter 6-storey adjacent building. Despite a 10 centimeter gap, the impact was strong enough to displace the steel-girder roof of the shorter building [1]. In the 1985 Mexico City and 1989 Loma Prieta earthquakes, a large share of seismic damage was also due to pounding. Pounding between adjacent structures has been generally modeled using a special spring-damper contact element, or the gap element, applying the principles of impact between rigid bodies and making use of a restitution factor [2]. An examination of the pounding of single-degree-of-freedom (SDF) systems showed that the response was not overly sensitive to the restitution coefficient [2]. Also, the intensity of impact was larger for adjacent systems with different heights. The risk of seismic pounding for buildings in Taipei was studied using contact spring elements [3]. The study showed that in 30% of the cases (708 cases out of a total of 2,359), the gap between buildings was not sufficient to prevent pounding. They predicted that in the case of a strong earthquake, 17% of studied buildings (403 cases) would be damaged, out of which 46 cases would collapse and 76 cases would be heavily damaged. Liolios [4] studied the problem of one-sided impact for adjacent buildings including friction. A numerical procedure based on an incremental problem formulation was utilized and a discretization in space and time was performed. Favvata et al. [5] investigated the storey-level impact between adjacent multi-storey buildings concentrating on the behavior of exterior steel beam-column connections. It was shown that, in certain cases, the localized nonlinear behavior of such connections could be beneficial for the associated columns by reducing their pounding damage. The pounding of base isolated structures was studied using a nonlinear Hertz element for modeling an inelastic impact [6]. The observation was that even for the base isolated buildings, pounding results in increased floor accelerations and displacements and activation of higher modes. Similar research was carried out on other base isolated structures focusing on the acceleration response of floors [7]. The seismic behavior of pounding buildings was investigated using lumped parameter gap elements [8,9]. In another work, it was reported that the period ratio of two adjacent structures determines the probability of occurrence of pounding [10]. For increasing period ratios, the risk of pounding was shown to be higher. Seismic pounding has been also extensively observed in bridges. In earthquakes such as San Fernando (1971), Loma Prieta (1989), Northridge (1994) and Kobe (1995), severe damage occurred due to pounding [11, 12]. However, in comparison to buildings, the problem of pounding for bridges has evidenced less consideration. The inclusion of a sufficient gap and the enlargement of expansion joints in bridges are expensive and usually impractical due to current traffic usage [12]. Pounding between adjacent structures having different structural properties during earthquakes has been the subject of other various research work [13-21], in which either the base has been taken to be rigid or through-the-soil interaction has been ignored. From these studies, some new findings have been obtained. For example, similarity in the frequencies of adjacent structures reduces the probability of pounding. Also, in order to avoid the incidence of pounding between adjacent buildings in base isolation cases, a greater distance is needed than that usually set out in non-isolated cases. In addition, it has been seen that column-to-floor pounding is more critical than floor-to-floor cases, and the pounding phenomenon is detrimental rather than beneficial and this is more intense for the taller adjacent building.

Structure-soil-structure interaction (SSSI) is another important seismic phenomenon occurring in closely spaced buildings [22]. According to early findings, SSSI increases the vibration period, and damping and lateral displacement results in a rocking motion in adjacent buildings [23]. When damping does not increase to the extent that it alleviates the effects of the increased period and the induced rocking motion, this combinatory phenomenon can result in an increased displacement response and a higher possibility for pounding even if the code prescribed distance is observed between buildings. Considering pounding and cross interaction concurrently is not usual in seismic analysis because high-accurate modeling of SSSI problems is particularly complicated. In recent works, researchers have tried to simplify the modeling of SSSI problems whilst preserving a sufficient level of accuracy, such as simple discrete models for the interaction of adjacent buildings [24-27] or the near-field method for the inelastic modeling of SSSI problems [28]. The interested reader may refer to the reference [29] where a comprehensive list of SSSI included studies could be found.

As discussed above, the complexity of simultaneously studying the seismic pounding of adjacent buildings and SSSI problems has resulted in a limited number of relevant research. The pounding of two adjacent structures on flexible foundations during the Montenegro earthquake was studied in [30]. It was shown that the foundation flexibility effects on pounding could not be ignored. Chouw [31] analyzed two adjacent buildings linked by a pedestrian bridge taking into account soil flexibility by employing the boundary element method. The majority studies on pounding-included structural adjacency cases has been carried out on bridge structures. For example, in a study on a bridge on soft soil with soil-structure interaction (SSI), it was concluded that the minimum distance at the expansion joint was a function of the shear wave velocity in soil [32]. In another work [33], it was observed that SSI can considerably increase the number of impacts between bridge girders under the effect of non-uniform ground motions. In two concurrent experimental works, SSSI effects on pounding were studied considering small scale bridge models resting on stiff, medium and soft soils using shake table tests [34, 35]. It was shown that pounding was more probable when the soil was softer and the two structures were more different in terms of fundamental period. The nonlinear behavior of the soil was observed to have an essential effect on pounding in bridges [36]. On such soils, the lateral displacements of adjacent decks were amplified and resulted in a larger impact. In another study [37], it was shown that the code-prescribed width of the separation joint is not sufficient on soft soils especially when the fundamental periods of the soil and structure were close to each other and also to the excitation frequency due to resonance phenomenon. Naserkhaki et al. [38] developed a model consisting of adjacent shear buildings responding in elastic range resting on equivalent springs and dampers. They observed that pounding and SSSI together resulted in a more severe response in terms of maximum shear and displacements of top floor.

The evident importance of cross-interaction between adjacent structures effects on pounding in addition to the scarcity of relevant literature on the subject constitute the main motivation behind the current research. The main importance of the current work stems from the emphasis on two major topics: (1) more accurate modeling of the problem geometrically as well as in terms of material nonlinearity; and (2) more reliable and quantitative investigation of the problem which would lead to more practical results. A series of numerical analyses on the SSSI-included seismic pounding of adjacent building structures has been carried out. The analysis is conducted on two symmetric building structures having various heights and considering the inelasticity of underlying soft soil profile and the nonlinearity in impact elements. To prevent the plane-strain assumption of the complicated SSSI study, 3D geometrical models have been developed in this study including underlying soil volume and two adjacent buildings subjected to uniaxial earthquake excitations.

Based on the aforementioned limitations (i.e. planar pounding between symmetric adjacent buildings), the torsional effects triggered by the pounding have not been taken into account. Therefore, the main goals of this research are: (i) Study the minimum distance for building separation recommended by the International Building Code (IBC) [39]; and (ii) Investigate the seismic pounding effects on damage distribution along the height of adjacent buildings, in both of SSI and fixed base (FB) conditions.

2. Design of structural systems

Four 3-dimensional (3D) buildings are considered here for developing various adjacency cases, two short (5 and 10 stories) and two tall (15 and 20 stories) buildings. The inter-storey height is equally 3 meters (*m*) which results in total heights of the buildings of 15, 30, 45 and 60 *m*, respectively. For each building, four bays (with length equal to 5 *m*) have been assumed in each direction in the stories and therefore the plan dimensions in all buildings are considered to be 20×20 *m*. The structures are located in a very high seismicity area. According to the ASCE7-2010 standard [40], the gravitational loads are DL = 7.60 kN/m^2 and LL = 2.00 kN/m^2, where DL denotes dead load and LL denotes live load. The load bearing system is a special steel moment frame designed based on AISC360-10 [41]. The diaphragms are RC rigid in plane slabs with a thickness of 0.15 to 0.20 *m*, with thicker slabs for the taller buildings. The structural sections used for the buildings are summarized in Table 1. Strip and mat foundations are used for the 5 and 10-storey buildings, respectively; however, for the tall 15 to 20-storey buildings pile group foundations are selected. The above foundation systems are all assumed to have a boundary area of 21×21 *m*. The length of each pile is 20 *m*. Table 2 shows the characteristics of the pile groups designed for each building and soil type D. Additionally, values of the first four natural vibration modes periods of each designed building in fixed base condition are presented in the Table 3.

Table 1. The typical sections of 5 to 20-storey buildings (units in mm, IPE*a* is an I section, *a* mm deep).

No. of Stories	***Beam Sections***	***Column Sections***
5	IPE300 and 330	Box240x12.5, 260x12.5 and 280x12.5
10	IPE300, 330 and 360	Box260x20, 280x20 and 300x20
15	IPE300, 300O, 330, 330O, 360 and 360O	Box180x20, 240x20, 300x20 and 340x20
20	IPE300, 300O, 330, 330O, 360, 360O, 2IPE300 and 2IPE330	Box200x20, 240x20, 260x20, 320x20 and 340x20

Table 2. Characteristics of the pile groups designed.

No. of Piles for Each Building		***Pile Diameter for Each Building* (m)**		***Pile Cap Thickness* (m)**
15S	***20S***	***15S***	***20S***	
16	16	0.5	0.6	1.0

Table 3. In-plane natural periods of the designed buildings (fixed base conditions).

No. of Stories	***T (sec)***			
	Mode 1	***Mode 2***	***Mode 3***	***Mode 4***
5	0.98	0.33	0.20	0.14
10	2.01	0.64	0.41	0.29
15	2.92	1.11	0.60	0.42
20	3.48	1.31	0.71	0.50

3. Site profiles considerations

A common site of soft soil is considered for the dynamic analysis. This soil profile consists of three clay layers with a total depth of 45 *m* on a bedrock [23, 28]. The properties of the soil profile are presented in Table 4. The effective values of the shear modulus *G* and the damping ratio ξ are taken into account for each soil layer.

Table 4. Properties of the soil layers (*Z*=depth, E=modulus of elasticity, G_{max}= static shear modulus, V_s= shear wave velocity, T_s= fundamental period, C_u= undrained cohesion) [23, 28].

***Z* (m)**	**C_u (kPa)**	***E* (kPa)**	**G_{max} (kPa)**	**V_s (m/s)**	**T_s (s)**
0 - 10	148	166,334	61,605	185	
10 -25	206	204,242	75,645	205	0.84
25 - 45	365	333,578	123,548	255	

Figure 1 shows the amplification curves of the above site obtained from ground-level earthquake records deconvolution procedures using the SHAKE2000 program [42]. As can be observed, the selected site will amplify the bedrock motions for the common frequency range of earthquakes at bedrock of 0.1-1 Hz. The dynamic characteristics of the sites presented in Table 4 and Figure 1 show that the selected soil profiles are general enough within the soil type D as per ASCE7 site classification provisions [40].

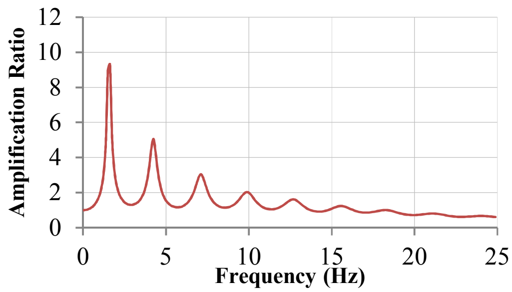


Figure 1. Amplification curves of the site.

4. Seismic records

A set of at least seven pairs of consistent earthquake records are necessary for dynamic analysis [40], if the average response is to be used. For consistency, the following conditions were taken into account in the selection of ground motions: site classification D, magnitude 6-7, source distance 20-50 kilometers (km) and strong motion duration ≥ 12 sec. The database of PEER NGA [43] was explored with the above constraints, and earthquakes cited in Table 5 were selected.

Table 5. Characteristics of the earthquake records selected [43].

Event	Year	Station	PGA (g)	Scale Factor			
				5 Storey	10 Storey	15 Storey	20 Storey
Imperial Valley-06	1979	El Centro Differential Array	0.431	1.36	1.44	1.51	1.58
Loma Prieta	1989	Hollister Diff. Array	0.264	1.80	1.89	1.99	2.08
Kocaeli, Turkey	1999	Duzce	0.326	1.35	1.42	1.49	1.57
Duzce, Turkey	1999	Duzce	0.427	0.97	1.02	1.07	1.12
Chi-Chi, Taiwan	1999	CHY036	0.260	1.60	1.69	1.77	1.86
Erzican, Turkey	1939	Erzincan	0.489	1.20	1.26	1.33	1.39
Imperial Valley-06	1979	El Centro Array #7	0.463	1.22	1.28	1.34	1.41
Loma Prieta	1989	Foster City - APEEL 1	0.291	1.76	1.85	1.95	2.04
Northridge-1	1994	Northridge -17645 Saticoy St.	0.411	1.33	1.40	1.47	1.54
Northridge-1	1994	Rinaldi Receiving St.	0.634	0.89	0.94	0.98	1.03

The scaling of the ground motions has been done based on the ASCE7-10 code design spectrum. The code recommends that the scaled mean acceleration response spectrum (at 5% damping) should not be less than the design spectrum over the periods ranging from $0.2T$ to $1.5T$, where T is the fundamental period (fixed base) of each building. Figure 2 shows the spectral accelerations of soil type D records after scaling for the 10-storey building (T=2.03 seconds). Moreover, a comparison with Figure 1 reveals that the selected earthquakes are powerful enough within the governing frequency range of the sites.

In this SSSI-included study, the earthquake records are input at the bedrock to the structure-soil-structure system. Therefore, in order to compute the ground motion at the bedrock, a free-field response analysis using SHAKE2000 program has been conducted beforehand where the above ground surface motions are input at the top of a 1-D free-field soil column. The considered column consists of the whole vertical profile of soil.

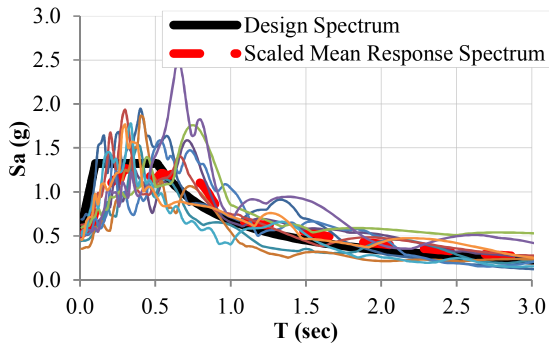


Figure 2. Design and scaled response acceleration spectra (5% damping) for the 10-storey building on soil type D.

5. Modeling considerations

The SSSI system is modeled in SAP2000 [44] for dynamic analysis. In the following subsections, the modeling considerations of the structure and the soil are presented.

5.1. Structural considerations

To comply with real behavior under large earthquake loading, the structures designed in Section. 2 are modeled nonlinearly for dynamic analysis of the SSSI. The nonlinearity is introduced in the structural members by placing elasto-plastic zero length hinge elements at the ends of the frame elements. These hinges are rigid before yielding and their moment-rotation behavior is schematically shown in Figure 3. This is a generic figure in which the quantities on the vertical and horizontal axes are normalized using appropriate scale factors (SFs). These scale factors are yield rotations of plastic hinges according to equation 5-2 in FEMA 356 [45] for steel structural members automatically defined in the SAP2000 program. The diaphragms and the pile caps are modeled by linear shell elements. The diaphragms are assumed to be rigid in plane.

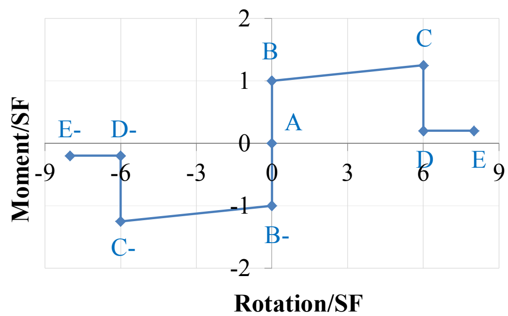


Figure 3. Schematic of the moment-rotation diagram of elasto-plastic frame hinges.

In Figure 3, B is the yield point and C is the capacity point after which the moment capacity drops sharply due to local failures (rupture or buckling). The length of line B-C is proportional to the rotation ductility of the hinge. The ordinates of the anchor points on the moment-rotation diagram in Figure 3 are extracted from ASCE41 [46]. The damping value of each structure is assumed to be of Rayleigh type with 5% material damping. For the soil media, the damping is considered using Near-Field Method presented in section 5.2. According to this method, the effective properties (effective damping and shear modulus) of soil are used in the far-field zone. In the near-field zones, modified values of the effective properties are used.

The damage index (*DI*) is the key parameter for the quantitative investigation of seismic pounding effects of nonlinear structural response. For an assessment of this parameter, a simple deformation-based non-cumulative equation (Equation 1) is presented as follows [47]:

$$DI = \frac{\Delta_t - \Delta_y}{\Delta_u - \Delta_y} = \frac{\dfrac{\Delta_t}{\Delta_y} - 1}{\dfrac{\Delta_u}{\Delta_y} - 1} = \frac{\mu_t - 1}{\mu_u - 1} \tag{1}$$

Where $\mu_t = \Delta_t/\Delta_y$ and $\mu_u = \Delta_u/\Delta_y$ are ductility demand (target displacement Δ_t to yield displacement Δ_y) and ultimate ductility (ultimate displacement Δ_u to yield displacement Δ_y), respectively. The values of Δ_y and Δ_u can be determined from pushover analysis separately for each storey. In this study, the pushover analyses have been carried out with the parameters defined according to FEMA 440 displacement modification [44] in SAP2000 software. The target displacements of the stories of each adjacent building (Δ_t) can be calculated from direct integration time history inelastic analyses using the scaled earthquake records presented in Table 5. In order to account for probable underlying soil effects, these pushover and dynamic analyses have been carried out on SSSI models including impact elements. From these defined parameters the value of *DI* for each storey can be determined according to Equation 1. The soil modeling considerations in the SSSI models are reviewed in the next sub-section.

5.2. Geotechnical considerations

The direct method of analysis of a system consisting of soil and structures is adopted in analyses of this study. In such analyses, the suitable plan dimensions of a certain volume of soil under structures limited to the bedrock must be selected. The plan dimensions of the soil (*L* and *B* in Figure 4) were determined by trial and error, as presented in reference [28]. Adequate values for these dimensions have been obtained to be as: $L=(100\ m + d)$, where d is the clear separation distance, and B=40 *m*. In fact, it has been observed that for at least $D_x=2.5a$ in *x*-direction and $D_y=0.5a$ in *y*-direction, the structural responses are numerically stable and independent of soil medium dimensions. Figure 5 shows a sample convergency analysis result.

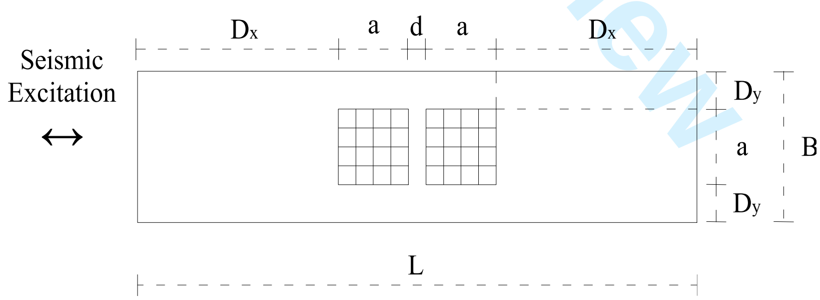


Figure 4. The geometrical dimensions in the site plan of adjacency model.

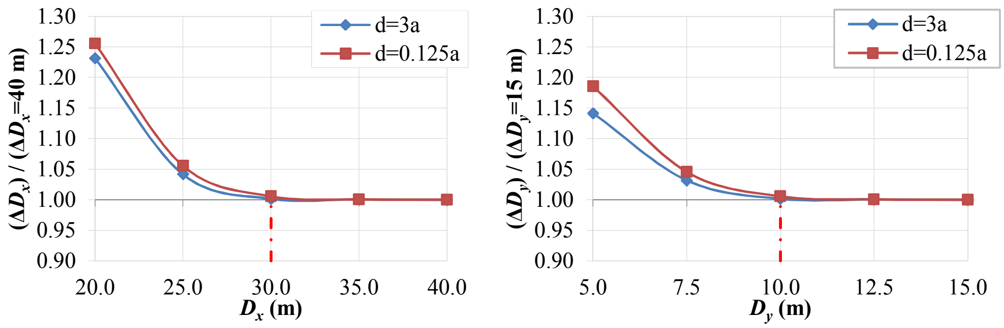


Figure 5. The lateral roof displacement for the case of the 30-storey adjacent buildings versus the dimensions introduced in Figure 4 (responses are normalized to the ones at the dimensions shown as indices) [28].

An extended equivalent linear method has been used for the modeling of nonlinearity and inelasticity soil material in site volumes called the Near-Field Method (NFM) [28]. The fundamental basis of NFM is presented in Figure 6. This figure presents an SSSI system containing two 15-storey adjacent buildings with a clear distance of 10 m resting on a soil medium. According to the NFM, this medium is divided into two separate soil zones called "Near-field" and "Far-field" that are in the vicinity of and far from the superstructure, respectively. In modeling the Far-field zone, the effective (initially reduced) soil properties determined in a free-field dynamic response analysis are used. For the Near-field zone, a secondary reduction is required to be applied on soil shear modulus, due to structural vibrations and inelastic soil-foundation interaction under earthquake excitation, which increase the cyclic soil shear strain values in the Near-Field zone. A rigorous numerical model has been presented in reference [28] to determine the near-field dimensions and also the effective properties of the soil medium.

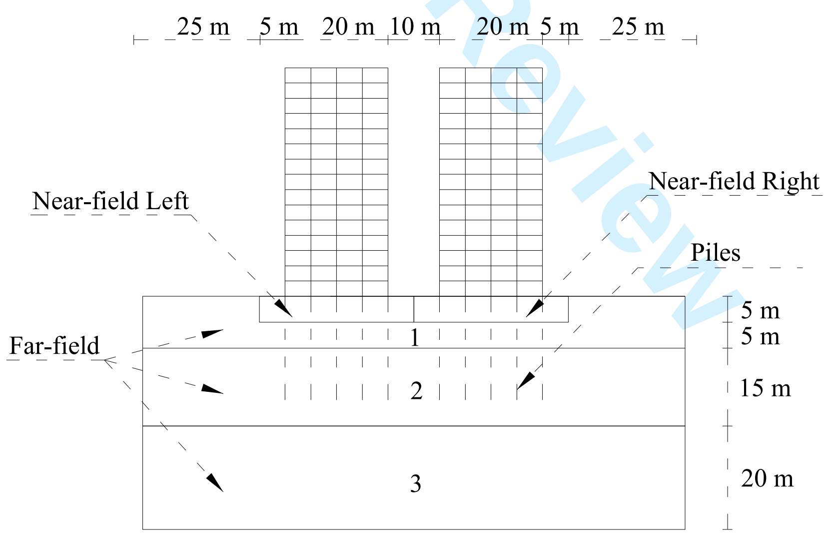


Figure 6. The near-field soil zone for two adjacent 15-storey buildings on the underlying soil medium.

5.3. Adjacency distance considerations

In the study of seismic pounding between two adjacent buildings that simultaneously including SSSI effects, it is required that the structures are close enough to each other to increase the seismic pounding occurrence probability. On the other hand, two adjacent buildings should not be so far away from each other that the SSSI effects are eliminated. An adequate clear distance between two adjacent buildings (d) must be limited to a minimum value equal to the minimum distance for building separation (δ_{MT} according to IBC 2009 standard) and also a maximum value equal to half of the greater adjacent building width in plan (a/2 where a is the greater adjacent building width [28]), which can be expressed as in Equation 2 below:

$$\delta_{MT} \le d \le \frac{a}{2} \tag{2}$$

According to IBC 2009 standard, δ_M shall be determined at critical locations using Equation 3 [39]:

$$\delta_{MT} = \sqrt{\left(\delta_{M_1}\right)^2 + \left(\delta_{M_2}\right)^2}$$
$$\delta_{M_i} = \frac{C_d \delta_{max}}{I} \qquad (i = [1,2] \text{ is the number of each adjacent building}) \tag{3}$$

in which C_d , δ_{max} and I are deflection amplification factor (as in Table 12.2-1 of ASCE7), maximum displacement (section 12.8.4.3 of ASCE7) and importance factor (section 11.5.1of ASCE7) respectively for each building. In this study, δ_{M_1} and δ_{M_2} are taken as the linear lateral displacements of adjacent buildings at the probable collision storey level. These values can be determined from linear time history analyses of the considered buildings in two SSI (according to chapter 19 provisions of ASCE7 standard [40]) and fixed base conditions. For comparison, δ_{M_1} and δ_{M_2} calculated in both of SSI and FB cases, are presented in Table 6. The labels of 5S, 10S, 15S and 20S denote the 5, 10, 15 and 20-storey buildings, respectively. The collision storey is taken as the location of the first probable collision between adjacent buildings; usually this is the top floor of the shorter building (as a result of this study can be seen in Sec. 6).

Table 6. Minimum distances for separation of considered adjacent buildings according to IBC 2009 provision in FB and SSI base conditions.

Adjacency Case	*Collision Storey No.*	*FB*		*SSI*		*Differences in % (SSI to FB)*
		δ_{MT} (cm)	*δ_{MT}/a*	*δ_{MT} (cm)*	*δ_{MT}/a*	
5S with 10S	5	35.3	0.018	39.2	0.020	11
5S with 15S	5	31.2	0.016	34.6	0.017	11
5S with 20S	5	30.0	0.015	33.6	0.017	12
10S with 15S	10	56.6	0.028	65.1	0.033	15
10S with 20S	10	49.0	0.024	57.3	0.029	17
15S with 20S	15	79.8	0.040	96.6	0.048	21

As can be seen from Table 6, the variation of recommended minimum distances in SSI and FB conditions (SSI/FB %) is rather noticeable, especially as the adjacent buildings heights increase. However, for consistency and for the results to be comparable, the same separation distances have been used in both of FB and SSI conditions. As the SSI condition is the main case and the FB condition is the secondary (i.e. for comparison purposes) case, the SSI column values from Table 6 are selected to be used for all of the models developed in this study. Hence, the adjacency distance values are as follows:

$$\begin{aligned} &0.02a \le d \le 0.5a && \textit{(for all cases that include adjacency to the 5-storey building)} \\ &0.03a \le d \le 0.5a && \textit{(for “10S with 15S” and “10S with 20S” cases)} \\ &0.05a \le d \le 0.5a && \textit{(for “15S with 20S” case)} \end{aligned} \tag{4}$$

These distance ranges for various adjacency cases stated in Equation 4 have been discretized to a sufficient number of interval values (5 values) as shown in Table 7.

Table 7. Minimum distances for separation of considered adjacent buildings according to IBC 2009 provision.

Adjacency Type	*Non-dimensional spacing intervals (d/a)*
5S with 10S	[0.02, 0.04, 0.08, 0.25, 0.50]
5S with 15S	[0.02, 0.04, 0.08, 0.25, 0.50]
5S with 20S	[0.02, 0.04, 0.08, 0.25, 0.50]
10S with 15S	[0.03, 0.06, 0.09, 0.25, 0.50]
10S with 20S	[0.03, 0.06, 0.09, 0.25, 0.50]
15S with 20S	[0.05, 0.10, 0.15, 0.25, 0.50]

5.4. Pounding considerations

The impact element model is shown in Figure 7 and consists of three sub-elements. In the middle part, a linear spring k_p, and a dashpot c_p are present. On the right, there is a predefined gap. The spring k_p is used for modeling elastic deformations at impact. The viscous damper c_p defines a linear source of energy dissipation (due to heat and sound) at impact. The element is activated when the gap is closed. In Figure 7, *i* and *j* signify the two nodes of the element. This element has an extension (contraction) degree of freedom at each node.

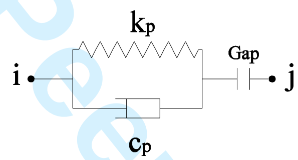


Figure 7. The pounding (impact) element.

The value of k_p depends on the stiffness of colliding bodies. As the pounding considered here is planar, adjacent rigid diaphragms of collision stories (having the same height) are assumed as the adjacent impacting bodies. The collision can be assumed between two adjacent rigid bodies and therefore k_p must be taken to be very large. The results of time history analysis conducted were insensitive to values $k_p \geq 10^{10}$ *N/m*, therefore $k_p = 10^{10}$ *N/m* is assumed. Figure 8 shows the effect of k_p variation on storey shear force for the case of two 10 and 20-storey adjacent buildings on soil with d=0.03a.

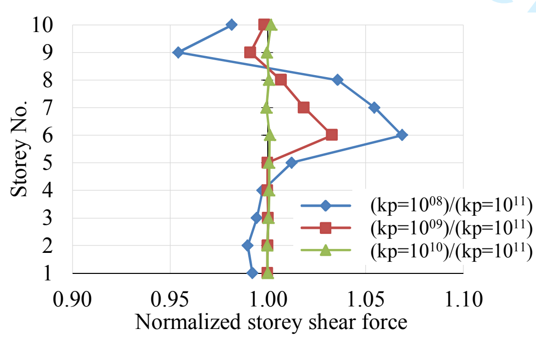
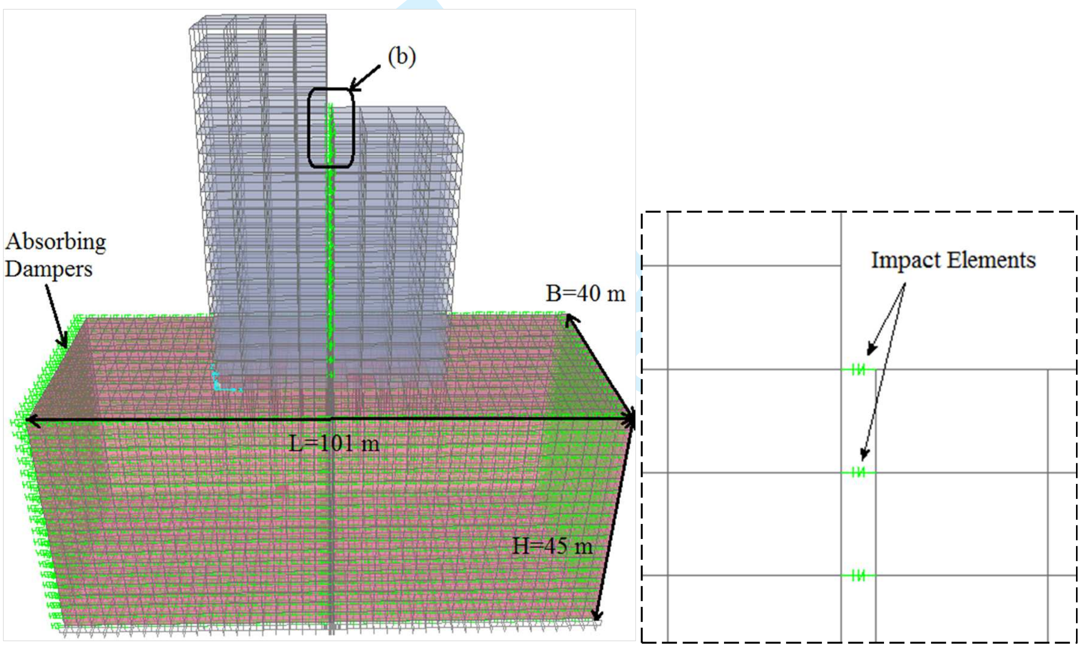


Figure 8. Storey shear force distribution in structural height in a 10-storey building adjacent to a 20-storey building with d=0.03a (i.e. d=1.0 m) (the values in each case have been normalized to the case of $k_p = 10^{11}$ N/m).

The value of damping coefficient c_p can be calculated from the literature (equation 5 in Ref. [2]) according to the damping ratio (ξ). For the applications herein, a value of the damping ratio ξ=0.14 has been assumed [2]. Also, the gap values are determined from Table 7.

5.5. Numerical modelling

The numerical models for the study of seismic planar pounding effects considering SSSI presented herein are 3D geometrical models developed with one-directional seismic pounding and assembling the two adjacent symmetric buildings, soil medium and impact elements between stories with the same heights subjected to uniaxial earthquake excitations. The impact elements have been considered in all of the adjacent stories (from bottom to top along the structural height of lower adjacent building). An example of the finite element (FE) model of the pounding case including two 15 and 20-storey buildings on flexible base with d=0.05a, abbreviated as 15S-20S-SSSI-0.05a case, made in SAP2000 software is depicted in Figure 9. The bottom of the model is rigidly fixed at the bedrock surface. The vertical side boundaries are selected to be of the transmitting type, where use is made of absorbing viscous dampers perpendicular to the boundary with damping factors $\rho V_s A$ in which A is the area shared by one damper, V_s is the shear wave velocity and ρ is mass density of soil [26, 48]. The earthquake records are only input at the bedrock to the structure-soil-structure system.



(a) (b)

Figure 9. 15S-20S-SSSI-0.05a case, (a) 3D FE model made using SAP200 (Soil boundary elements are energy absorbing dampers [26, 48]), (b) Cross section of impact elements between adjacent stories (These elements are located between two buildings at all adjacent stories along the height of buildings).

6. Results

As aforementioned, the current research aims to investigate two main issues considering SSSI-included pounding namely:

1) Minimum distance of adjacent buildings for pounding prevention.
2) Pounding effect on structural seismic damage.

In the following sections, the distribution of impact elements forces and the seismic response of adjacent buildings are presented. In this study, The dynamic analyses were conducted for 10 earthquake excitations but only mean values of the results will be presented In this section.

6.1. Minimum distance of adjacent buildings for pounding prevention

During an earthquake, it is possible that two adjacent buildings extremely approach each other without a significant impact. Therefore, the investigation of envelop values of seismic gap time history of impact elements cannot be an adequate indication for the occurrence of strong seismic pounding. The pounding phenomenon can be directly investigated according to envelop values of spring force time histories of impact elements. In order to study these forces, the best method is to investigate the storey shear force distribution along the height of one of the adjacent buildings (for example, the taller building) with and without the presence of impact elements (Figure 9) in various adjacency cases. The observation of considerable change in storey shear forces in the presence of impact elements in comparison to the case without these elements would mean a severe seismic pounding occurrence. In addition, an investigation of probable pounding effect on storey shear force is provided hereinafter. Figures 10-12 show results for all adjacency cases including SSSI effects and FB conditions. In these figures, the horizontal axes indicate normalized storey shear force in the presence of pounding elements (V) to their values in the absence of these elements (V_0) and the vertical axes indicate the number of stories. Reviewing these figures, some important observations can be made:

1- As expected, the most critical adjacency distance is the minimum value recommended by the IBC 2009 standard (i.e. minimum value of d in Eq. 4) and leads to maximum variations in storey shear forces.

2- Due to pounding, the maximum variation in shear forces of the taller building is always observed in the inter-storey above the top-floor of the shorter adjacent building. This floor is always the location of the first probable collision between the two adjacent buildings and therefore (in this study) is considered as the *collision storey* (this has been previously presented in Table 6). The above inter-storey in taller buildings experiences the maximum variation in shear force during seismic pounding and can be considered as the *critical storey*. This outcome has been confirmed for shorter buildings through similar results including the distribution of storey shear forces in each adjacency case; however, for the sake of brevity their results are not presented in this paper.

3- If a significant pounding is quantitatively taken as the pounding with more than 10% variation in collision storey shear force, significant seismic pounding can be observed in all SSSI-included adjacency cases taking into account IBC 2009 recommended distance. Although soil-structure interaction has been taken into account as per ASCE7 in calculating the IBC 2009 recommended minimum distance for building separation, it is clear from the results presented herein that considerable pounding is easily possible during a strong earthquake for buildings on soft soils.

4- It seems that the “adjacency type” is an important issue in the study of seismic pounding effects on the response of adjacent buildings. For example, for each taller building as a target building, the critical effect of pounding with maximum variation in storey shear forces is observed in the case of adjacency with a shorter building having half the height of the target building (10S next to 20S and 5S next to 10S). For shorter adjacent buildings with heights less than this value, the seismic vibrations reduced considerably; consequently, the severity of the probable pounding is reduced (e.g. 5S or 10S next to 20S). For shorter adjacent buildings with heights more than this value, the pounding occurrence probability is significantly reduced (e.g. 15S next to 20S and 10S next to 15S), possibly due to similarities in the vibration frequencies and mode shapes to the taller building.

Based on the observations above, a more reliable recommendation for minimum distance of adjacent buildings to prevent probable seismic poundings can be suggested. The recommended adjacency distance can be selected as a conservative value of a variation boundary in shear forces of the critical storey in SSSI-included cases, Figure 13. This value is called the "baseline variation" and is selected to be 2.5% and its boundary has been highlighted as a vertical black line in the figure. According to Figure 13, the separation distance (d_{min}) must be selected in the range of 0.06*a* to 0.13*a*, depending on adjacency type. These distance values with IBC recommended minimum values are comparatively presented in Table 8. For each adjacency type, a minimum distance of more than 3 times the IBC/ASCE7 recommended value is required to prevent the seismic pounding of adjacent buildings resting on soft soils, Table 8. Also, it is necessary that the ASCE7-2010 chapter 19 soil-structure interaction provisions are considered when the IBC provision is used.

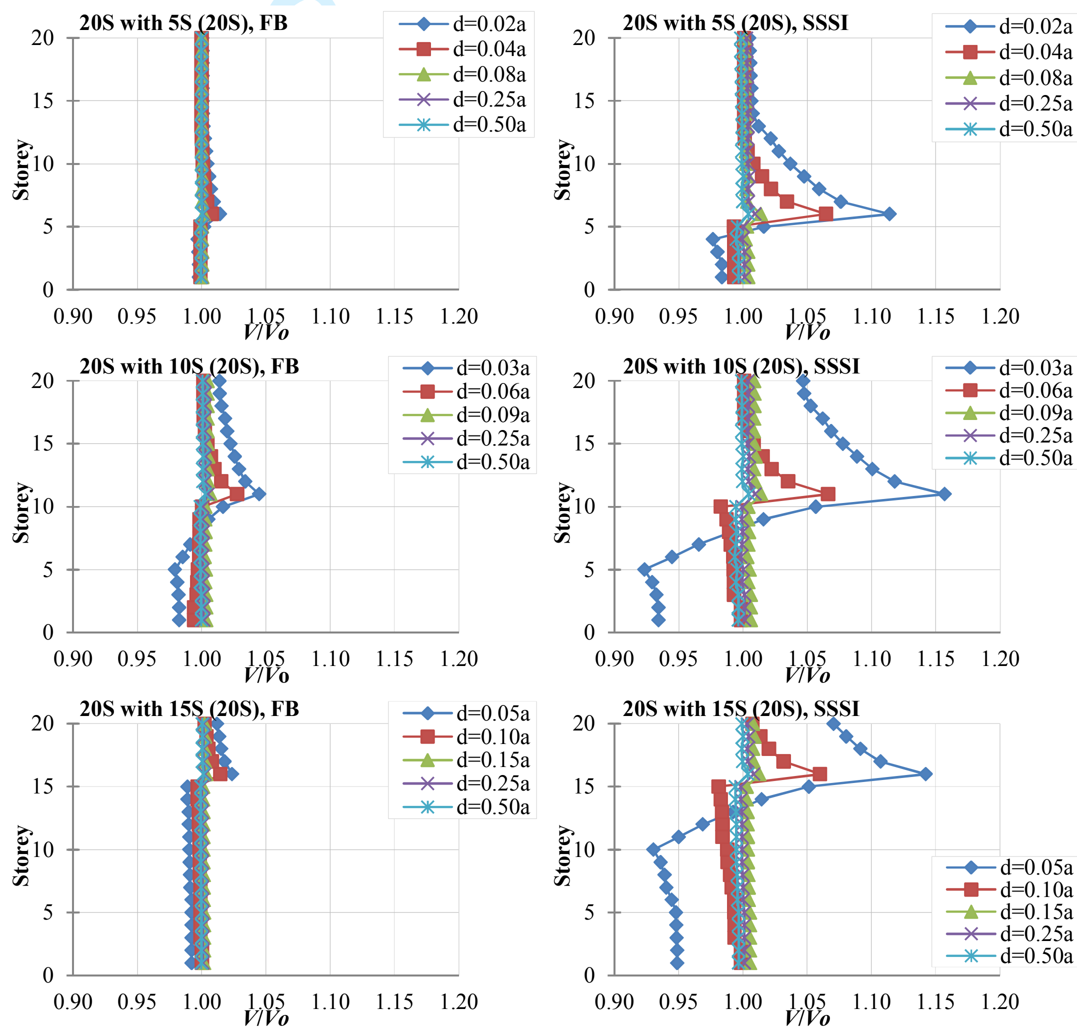


Figure 10. Normalized storey shear force in presence of pounding elements (V) to their values in absence of these elements (V_0) in 20-storey building adjacent to shorter buildings with various clear distances and base conditions.

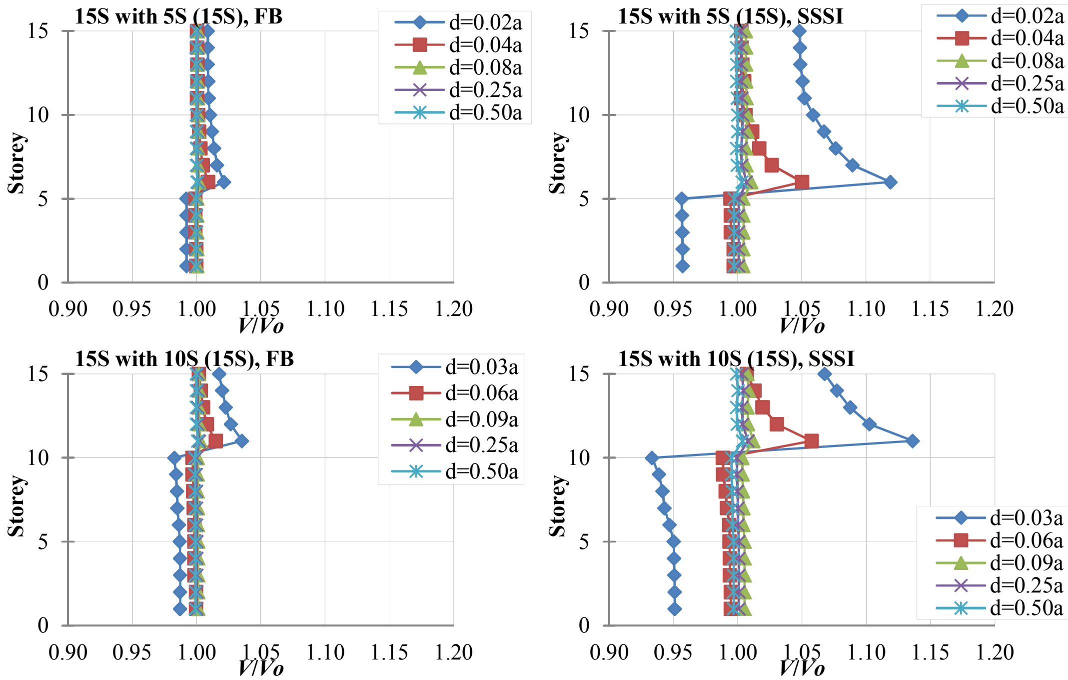


Figure 11. Normalized storey shear force in presence of pounding elements (V) to their values in absence of these elements (V_0) in 15-storey building adjacent to shorter buildings with various clear distances and base conditions.

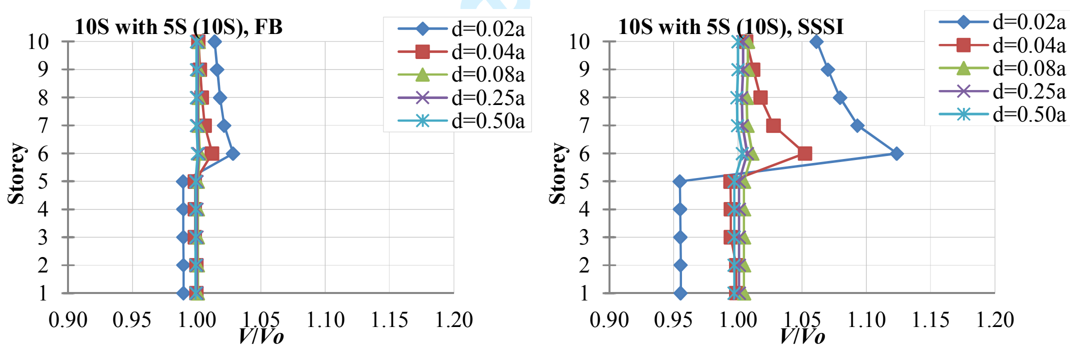


Figure 12. Normalized storey shear force in presence of pounding elements (V) to their values in absence of these elements (V_0) in 10-storey building adjacent to shorter buildings with various clear distances and base conditions.

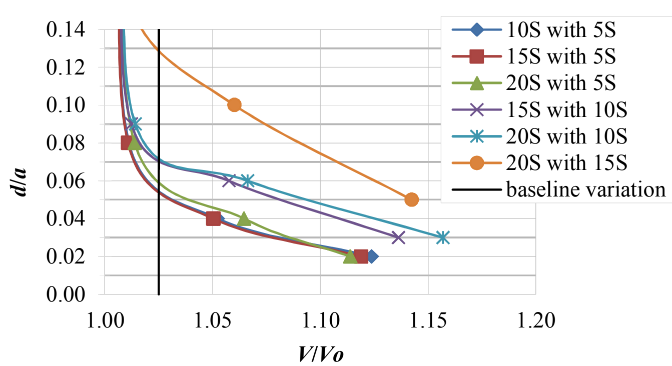


Figure 13. The variations of the normalized shear forces of the critical storey in presence of pounding elements to their values in absence of these elements in various SSSI-included cases.

Table 8. Minimum required distance for building separation and seismic pounding prevention on soft soils according to analyses in this study and IBC/ASCE7 standards.

Adj. Type	**d_{min}/a**		
	Current Analysis	**Codes (IBC & ASCE7)**	**Percentage of difference (%)** (Analysis-Codes)/Analysis x 100.
5S with 10S	0.0550	0.0200	64
5S with 15S	0.0550	0.0200	64
5S with 20S	0.0600	0.0200	67
10S with 15S	0.0725	0.0300	59
10S with 20S	0.0750	0.0300	60
15S with 20S	0.1300	0.0500	62

6.2. Pounding effect on structural seismic damage

In this subsection, the local and global effects of seismic pounding on the distribution of the damage index parameter (*DI*) along the height of adjacent buildings are investigated. The damage indices in the presence of impact elements have been normalized to their values without the presence of these elements (DI/DI_0). The clear distances equal to the minimum value recommended by the IBC/ASCE7 standards (Table 6 in the SSI case) were selected. The results including seismic damage distributions in all stories are presented in Figures 14-16. Reviewing Figures 14-16 and Table 9 the following interpretations could be stated:

1- The overall trend in the variation of seismic storey damage indices along the structural height is generally similar to that of storey shear forces. Also, as can be seen from Table 9 the variation in *DI* values during seismic pounding can be up to 48% and therefore is more significant than variation in *V* values, up to 16% (Figures 10-12). This result clearly indicates that the seismic damage index is a more sensitive parameter than the other conventional seismic structural response parameters and should be taken into account.

2- As would be expected, the inclusion of SSSI in studying the effect of pounding on seismic damage is considerable. The variation of normalized *DI* values due to this effect is up to 23% and 14% in taller and shorter building, respectively. Comparing the SSSI and FB curves in Figures 14-16, it can be observed that the SSSI increases the power and severity of the seismic impact and makes its effects more intense on structural seismic damage.

3- According to variations of DI/DI_0 especially at the critical storey for the fixed-base conditions, the IBC 2009 minimum separation distance was insufficient to prevent the occurrence of severe seismic pounding.

4- As previously stated, the *critical storey* always experiences the most variations in the seismic damage index (up to 48% and 20% in SSSI and FB conditions, respectively) due to the pounding effect in both of the adjacent buildings. For the shorter building, the maximum variation is observed at the top floor (up to 34% and 17% in SSSI and FB conditions, respectively). These significant variations have taken place when the IBC/ASCE7 recommended adjacency distance was selected.

5- During pounding the taller building experiences more seismic damage than the other building. Therefore, the pounding phenomenon is more critical for the taller adjacent building. The results observed for the tallest building (20-storey) considered in this study are summarized in Figure 17. For a tall building (with a total height of *H*) within close distances, it seems that the most critical case is adjacency to a shorter building with the height equal to *H*/2. A justification similar to that mentioned in item#5 in the previous section, can be presented for this observation. For shorter adjacent buildings with heights less than this value, the seismic vibrations reduced considerably; consequently, the severity of the probable pounding is reduced (e.g. 5S or 10S next to 20S). Also, for shorter adjacent buildings with heights more than this value, the pounding occurrence probability is significantly reduced (e.g. 15S next to 20S and 10S next to 15S), possibly due to similarities in the vibration frequencies and mode shapes to the taller building.

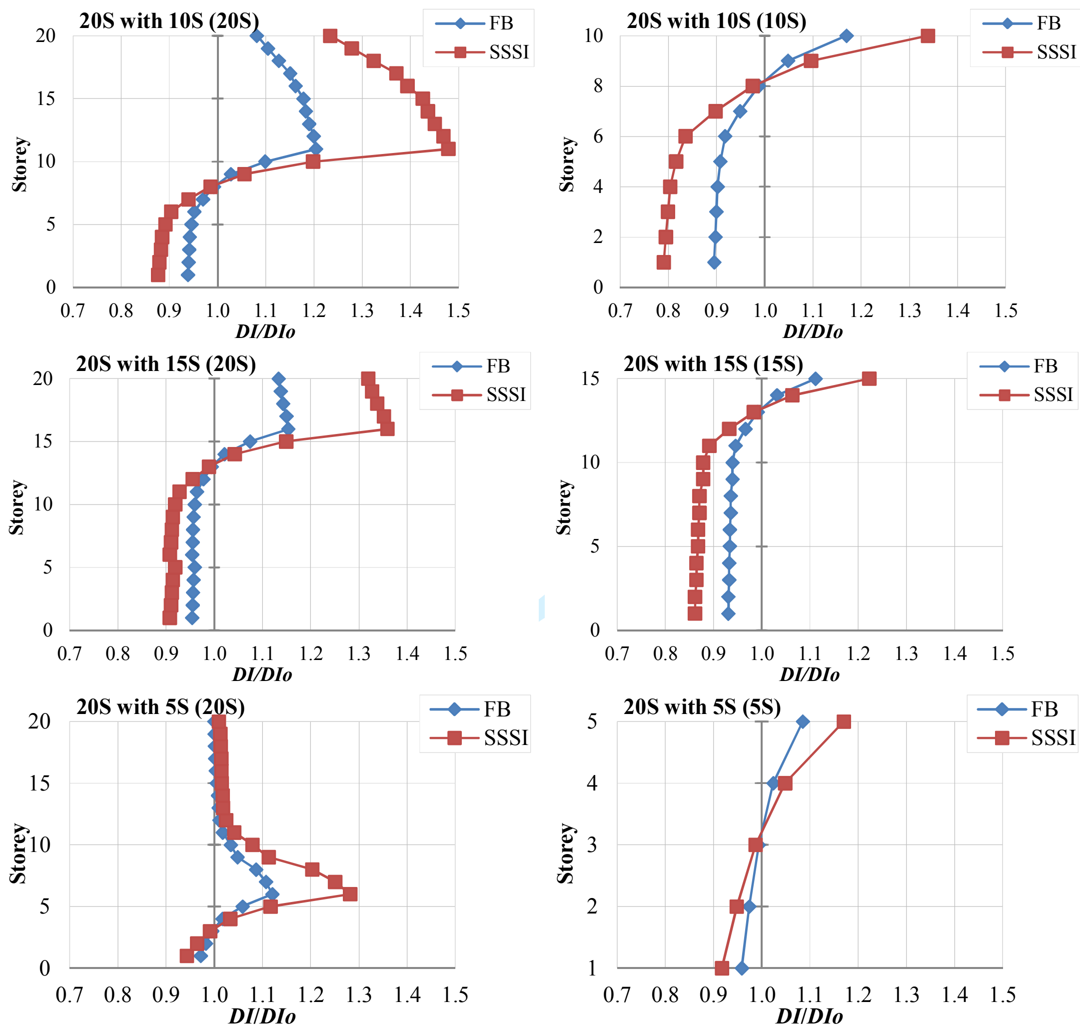


Figure 14. Normalized storey seismic damage index values in presence of pounding elements (*DI*) to their values in absence of these elements (DI_0) in two adjacent buildings of all 20-storey adjacency cases with *d*=IBC/ASCE7 recommended value in two FB and SSSI base conditions.

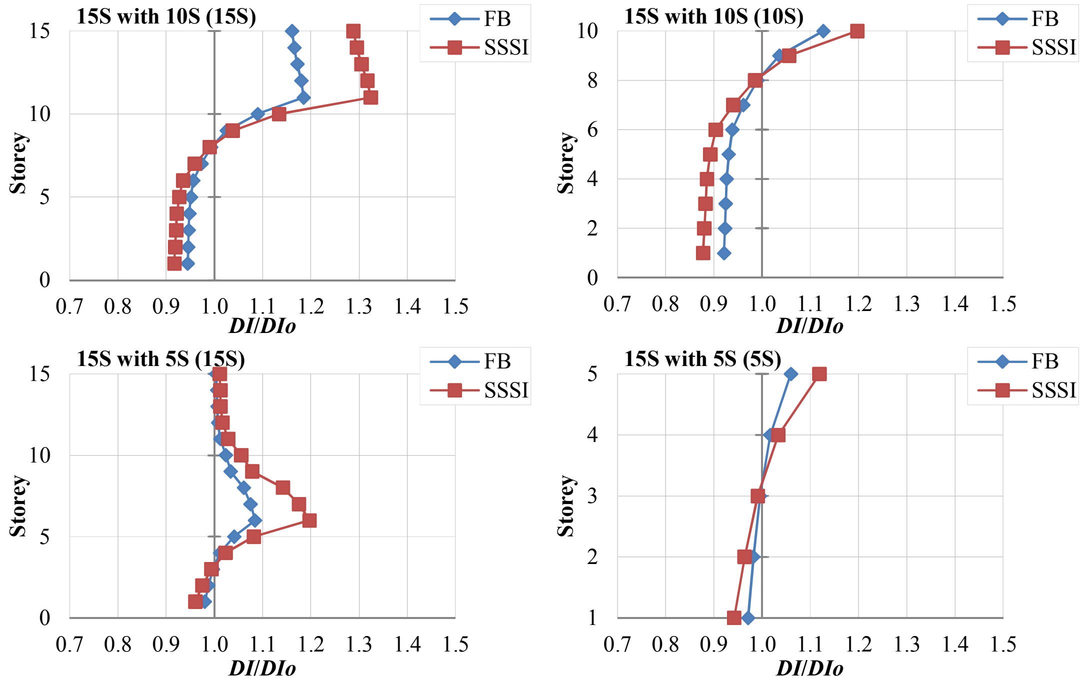


Figure 15. Normalized storey seismic damage index values with presence of pounding elements (DI) to their values with absence of these elements (DI_0) in two adjacent buildings of 15-storey building adjacency cases with shorter buildings with d=IBC/ASCE7 recommended value in two FB and SSSI base conditions.

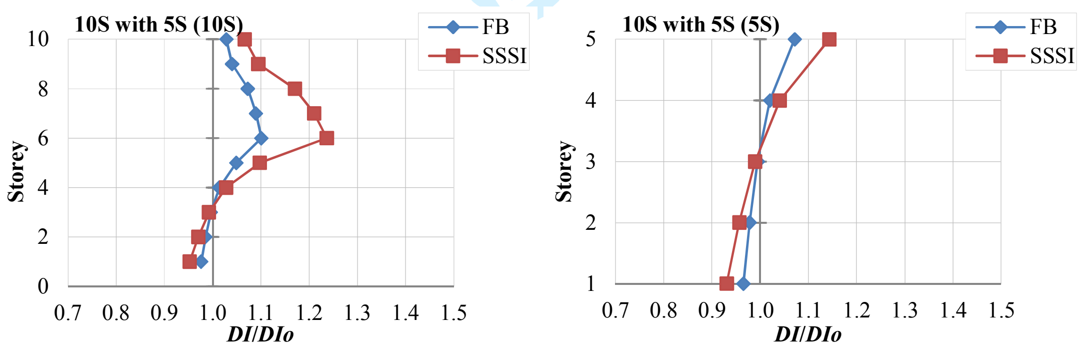


Figure 16. Normalized storey seismic damage index values with presence of pounding elements (DI) to their values with absence of these elements (DI_0) in adjacent buildings in adjacency case of two 10- and 5-storey buildings with d=IBC/ASCE7 recommended value in two FB and SSSI base conditions.

Table 9. Details of maximum variations of normalized storey seismic damage indices (observed in the critical storey) in presence of pounding elements to their values in absence of these elements in all adjacency cases with d=IBC/ASCE7 recommended distance for building separation.

Adj. Case	*Taller Adjacent Building*		*Differences in % (SSSI to FB)*	*Shorter Adjacent Building*		*Differences in % (SSSI to FB)*
	FB	*SSSI*		*FB*	*SSSI*	
	DI/DI_0 max	*DI/DI_0 max*	*(%)*	*DI/DI_0 max*	*DI/DI_0 max*	*(%)*
20S with 10S	1.20	1.48	23	1.17	1.34	14
20S with 15S	1.15	1.36	18	1.11	1.22	10
20S with 5S	1.12	1.28	14	1.09	1.17	8
15S with 10S	1.18	1.32	12	1.13	1.20	6
15S with 5S	1.08	1.20	10	1.06	1.12	6
10S with 5S	1.10	1.24	12	1.07	1.14	7

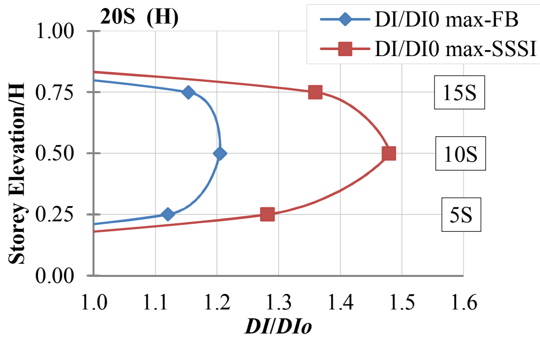


Figure 17. The envelope of the maximum seismic damage index variations at critical storey in 20-storey building based on the various impact locations due to adjacency to 5, 10 and 15-storey buildings.

6- If the clear distance between two adjacent buildings on soft soil is selected to be at least 3 times that of the IBC/ASCE7 recommended value, it can be expected that the maximum effect of seismic pounding on storey shear forces will be less than 2.5%. This observation can be investigated based on the seismic *DI* values as a more sensitive parameter in inelastic structural response. In Figure 18, the variation of the DI/DI_0 ratio at the critical storey in all SSSI-included adjacency cases with d=[3×(IBC/ASCE7 recommended distance)] are presented. As can be seen from Figure 18, negligible variations of seismic damage indices values are observed at this adjacency distance (up to 4%).

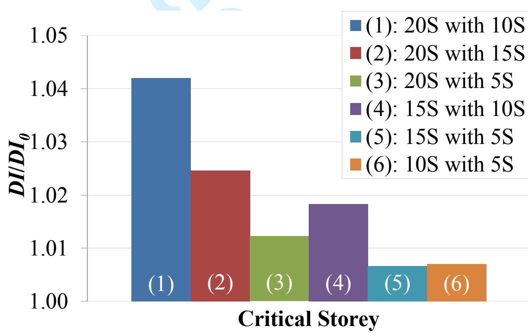


Figure 18. Variation in DI/DI_0 ratio at the critical storey in all SSSI-included adjacency cases with d=[3×(IBC/ASCE7 recommended distance)].

7. Conclusions

In this study the probable seismic pounding effects on the response of adjacent symmetric buildings considering structure-soil-structure interaction have been investigated. This was carried out by taking into consideration two adjacent symmetric in plane buildings excited by earthquake loadings on a soft soil profile representing the flexible base conditions. The inelasticity of structures and soil medium were taken into account by means of plastic hinge elements and the near-field method, respectively. The seismic damage index and shear force of stories were considered as the main structural system response measures. The pounding and SSSI phenomena as primary and secondary factors causing variations of structural seismic response in various adjacency cases were modeled both simultaneously and separately. Finally, within the assumptions considered in this study, some major observations can be made:

1-At least three times the IBC 2009 minimum distance for building separation recommended value is required as a clear distance for adjacent in-plane symmetric buildings (with identical architectural plan and dimensions) on soft soils to prevent the occurrence of seismic pounding. Within this distance, the maximum effects of the phenomenon are not more than 2.5% and 4% in terms of storey shear forces and seismic damage indices, respectively.

2-Seismic damage index (*DI*) is a more sensitive and critical parameter than conventional seismic storey shear and therefore should be given more significance.

3-In accordance with the IBC 2009 recommended minimum distance, buildings experienced severe seismic pounding and therefore significant variations in storey shear forces and damage indices of up to 16% and 48%, respectively, were observed at the *critical storey* in SSSI cases. The corresponding variations for the FB cases are 4% and 20%, respectively, for storey shear forces and damage indices.

4-The taller adjacent building experienced more severe seismic damage due to pounding than the shorter building. The location of the occurrence of this damage is not at the collision storey but at an inter-storey above that in the taller building termed the *critical storey*. The *collision storey* is the location of the first probable seismic pounding and is always the top floor of the shorter building.

5-For each tall building with a total height of *H*, during seismic pounding within a close adjacency distance, the most severe impact is powered by a shorter adjacent building with a height of *H*/2. For shorter buildings of height more than *H/2*, the similarity in vibration frequencies and mode shapes of buildings decreases the probability of the seismic impact. While for shorter adjacent building with the height less than *H/2*, a weak impact was observed. It is necessary to note that the architectural plan and storey height of adjacent buildings are assumed to be similar in this study and the only difference between the two considered adjacent buildings is the number of stories and therefore their total height. In general, the problem of "the effects of the vibration modes and frequencies on the pounding response of adjacent buildings" is an important issue that deserves further study. For such studies, it is suggested that more various types of buildings adjacency be considered and the effects of a parameter such as "adjacency frequency ratio" (the fundamental frequency ratio of adjacent buildings) on the seismic pounding response of taller adjacent building be investigated.

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